Title
The final technical report of the CRADA, Medical Accelerator Technology

Authors
Chu, William T.
Rawls, John M.

Publication Date
2000-06-12

SC LTR CRADA

The Final Technical Report

Project Title: **Medical Accelerator Technology** (SC-LTR No. BG94-094; LBNL #4504)

Principal Investigators:

National laboratory: William T. Chu

MS 71-259, Lawrence Berkeley National Laboratory, UC, Berkeley, CA 94720

tel. 510.486.7735; fax 510.486.5788; e-mail wtchu@LBL.gov

Industrial partner: John M. Rawls

General Atomics, MS 13-171, 3550 General Atomics Court, San Diego, CA 92186-9784

tel. 619 455 4340; fax 619 455 4341; e-mail john.rawls@gat.com

Project Period: July 1994–December 1999

Report date: June 12, 2000

Background:

For more than four decades, under the auspices of DOE, Berkeley Lab pioneered and developed technologies of treating human cancer using accelerated heavy charged-particle (proton and heavier ion) beams. To distinguish this modality from conventional radiation therapy that relies on gamma rays and electrons, clinical community now calls this field the "hadron therapy." In 1991 the first hospital-based medical proton accelerator facility was built in southern California, and two more were built during the CRADA period. Now more than eight hospital-based facilities are being built worldwide by commercial firms. Although the southern California facility was build by national laboratories working with industry, the subsequent facilities are being built as a turnkey system by the private sector, and the latter trend will continue.

Under this CRADA, Berkeley Lab and the industry partner, General Atomics (GA) of San Diego, have cooperatively developed hadron therapy technologies for commercialization. GA is the major U.S. firm of an industrial consortium that is building a proton therapy facility at the Northeast Proton Therapy Center (NPTC) of the Massachusetts General Hospital (MGH) in Boston.

Rationale for choosing GA as the Industrial Partner:

At the time of submitting the CRADA application (4/93), the U.S. firm to participate in building the MGH facility was unknown. To provide fairness of opportunity to participate in this CRADA, Berkeley Lab contacted all U.S. companies interested in building technical components of proton medical facilities. They were: AccSys Technology, Brobeck Division of Maxwell

Laboratories, General Atomics, Grumman Aerospace Corp., International Proton Systems, Science Applications International Corporation, Titan Beta, Varian Associates, and Westinghouse Electric Co. Berkeley Lab has discussed the opportunity with all these firms. In due course, MGH has picked GA as its contractor, and this CRADA was written with the only U.S. firm remaining in the MGH project.

GA and Berkeley Lab have a long history of successful collaboration in accelerator-related fields. Berkeley Lab did the engineering development of the high current accelerators used to heat Tokamak plasmas in GA's fusion research program; 20 MW of such equipment is still in use at GA, more than 15 years after the pioneering work was completed at Berkeley Lab.

During the duration of the CRADA, GA had more technical staff members involved in the design and development of accelerators and accelerator technology than any other firm in the United States. In addition to this CRADA in medical accelerator technology, GA has full responsibility for the accelerator for the Accelerator Production of Tritium program, the nation's largest current accelerator development program. Boron Neutron Capture Therapy (BNCT) and food irradiation are the two long-term applications of accelerators that receive major corporate support.

CRADA Mission:

Under this CRADA, Berkeley Lab and the industry partner, GA, have cooperatively developed hadron therapy technologies for commercialization. Specifically, Berkeley Lab and GA jointly developed beam transport systems to bring the extracted protons from the accelerator to the treatment rooms, rotating gantries to aim the treatment beams precisely into patients from any angle, and patient positioners to align the patient accurately relative to the treatment beams. We have also jointly developed a patient treatment delivery system that controls the radiation doses in the patient, and hardware to improve the accelerator performances, including a radio-frequency ion source and its low-energy beam transport (LEBT) system. This project facilitated the commercialization of the DOE-developed technologies in hadron therapy by the private sector in order to improve the quality of life of the nation.

CRADA Achievements:

The development of a proton therapy facility is a complex technological task as it involves developing diverse technical components to perform various functions, such as:

- proton acceleration
- beam transport from the accelerator to the patient irradiation rooms
- accurately and reliably directing the beam into the patients from any angle
- modification of the proton beam to make it suitable for treating cancer targets
- monitoring and control of the treatment delivery
- patient and personnel safety

The CRADA goals have been met in many different ways. In this report we will divide the methodologies into the following four parts:

1. Collaborative R&D in designing technical components of the proton therapy facility

Under this CRADA, Berkeley Lab critically reviewed the GA's engineering designs of the proton beam-line optics, rotating gantries, and patient positioners. Interactions between Berkeley Lab and GA through frequent meetings and reviews have provided transfer of technology necessary to solve critical problems that are central to achieving technically superior and cost-effective proton therapy. The technical components addressed in the CRADA include:

- Beam Transfer System (BTS):
  - Quadrupole and 30-degree dipole magnets
  - BTS controls, diagnostics, and safety system
- Patient positioner System (PPS):
  - Two PPS were designed, fabricated, installed at NPTC, and tested. The PPS has very good accuracy (<0.5 mm) and superb repeatability (≈70 µm). (See: G. Silke, L. Nissley, T. Hurn, Roger Junge (General Atomics); Y. Jongen, S. Laycock (Ion Beam Applications), "An Advanced Six-Axis Patient Positioner for use in Proton Therapy," presented at the 7th ANS Topical meeting on Robotics and Remote Systems, 1998.)
- Rotating Gantry:
- The rotating gantry was designed by GA.
  - 135-degree dipole magnets were designed, fabricated, installed on a gantry and tested at NPTC.
  - 45-degree dipole magnets were designed, fabricated, installed on a gantry, and tested at NPTC.

Furthermore, we have designed a radio frequency (rf) driven multicusp ion source for a 13.56 MHz operation with high proton percentage. The ion source has been designed, fabricated, and tested. An ion-optics computation was done and performance comparison was made among various electrode configurations of an electrostatic low-energy beam transport (LEBT) system. In our final design, the LEBT system consists of six electrodes, and can accelerate both 35 mA and 72 mA protons by adjusting electrode potentials without changing the mechanical parts. This newly-designed LEBT system conformed to the acceptance parameters of the Loma Linda type radio-frequency quadrupole (RFQ) with the proton beam accelerated to 35 keV. The ion-source-LEBT system developed under this CRADA is versatile and can be applied to different RFQ structures. We have jointly developed a complete engineering design report on the LEBT System. (See: D. Chen, W. Chu, J. James, G. Jones, Y. Lee, K.-N. Leung, R. Low, and D. Williams, "Electrostatic Low Energy Beam Transport (LEBT) System for Proton Therapy," Plasma and Ion Source Group, Lawrence Berkeley National Laboratory, September 1999.)

2. Direct transfer of technical know-how from the national lab to the industrial partner

At GA's request, Berkeley Lab has made available a complete quadrupole magnet design package (used in a prior facility to construct the Advanced Light Source at Berkeley Lab), including drawings and specifications which, with slight modifications, have been integrated into the GA product line. Quadrupole magnet laminations from thin sheet stock were successfully punched using the die supplied by Berkeley Lab. Quadrupole magnets were fabricated by the industry using the design and hardware provided by Berkeley Lab. These tools greatly shortened the quadrupole magnet schedule and enhance the effectiveness of factory testing of the hardware produced. Using this proven hardware has provided a significant risk reduction to the product development by GA.

3. Training of the industrial partner personnel

Under this CRADA, Berkeley Lab provided GA with computational tools in proton beam optics design; Berkeley Lab trained several GA scientists to utilize the beam optics code to calculate the proton beam propagations and beam losses in channeling magnets. Berkeley Lab also trained the GA personnel in fabrication technique of magnets for the proton beam transport system. Berkeley Lab has provided GA the hardware designs and "know-how" to accurately position and align magnets and sensors in the beam line using proven hardware and alignment technique.

4. Industry/national laboratory collaboration in installation and testing of technical components of the proton therapy facility

Our industrial partner, GA fabricated proton beam transport systems and patient positioners. GA produced the engineering design of a rotating gantry. After this hardware, as well as the cyclotron and other technical components, were installed at NPTC in 1998, Berkeley Lab and GA jointly worked on the integration and testing of these components.

CRADA Benefit to DOE and LBNL:

Under the CRADA, we have transferred the DOE-developed medical accelerator technology to the private sector. The general public is the ultimate beneficiary as it will result in improved health care. *"Accelerators for cancer cure"* will clearly be understood by the public. Returning the fruits of Federally-funded research from the national laboratory to society exemplifies the rationale of supporting basic science research at national laboratories. This CRADA enhanced the public support of the Federally-funded research at national laboratories.

This CRADA enabled Berkeley Lab to retain scientific personnel in the field of medical applications of particle accelerators. It made it possible for Berkeley Lab to propose several DOE FWPs in the related areas. A notable example is an FWP approved by DOE/OBER on "Accelerator-based BNCT clinical trial." DOE has also approved an Initiative for Proliferation Prevention (IPP) project, "Development of Neutronics Computational Tools for Medicine and

Industry." This IPP project is a joint project among Berkeley Lab, General Atomics, Industrial Partner, and NIS institutions, Institute of Physics and Power Engineering (IPPE), Obninsk, All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), Sarov, and Medical Radiological Research Center (MRRC), Obninsk, Russia. Without the medical accelerator resources at the Laboratory, initiation of this project would have been difficult if not impossible.

CRADA Benefits to the Industrial Partner:

Through the CRADA, GA obtained the expertise residing in a national laboratory. This CRADA has enabled a US firm to deliver to a private hospital a most advanced proton facility based on the DOE-developed technologies, enhancing the competitiveness of the US firm in the international market.

On 22 Jun 2000, Thomas Hurn of GA <thomas.hurn@gat.com> wrote to W. T. Chu, P.I., "It was a pleasure working with you and your talented scientists and engineers at LBNL on this CRADA. They greatly improved our ability to meet the challenges of the program. I hope we have the chance to collaborate on projects like this in the future."

CRADA Benefits to the Public:

The potential payoffs of the CRADA are substantial in terms of improving the quality of life through reducing cancer mortality.

Commercialization of the Proton Therapy Technology:

<u>The Status of the NPTC Proton Therapy Facility (6/2000)</u>:

All hardware components have been installed and integrated to form a complex proton therapy facility. (See: Y. Jongen, S. Laycock, et. al. (IBA); T. Hurn, L. Nissley, E. Hubbard, M. Heiberger, M. Tabor, G. Silke (GA), Toshiki Tachikawa, Masami Sano, et. al. (Sumitomo Heavy Industries), "The Proton Therapy System for MGH's NPTC: Equipment Description and Progress Report," 1998.) The commissioning has been delayed to the year 2001 due to the problems with the development of the treatment delivery software, which is outside the scope of this CRADA.

Award and Recognition:

On May 10, 2000, the P.I. of this CRADA, Dr. William Chu of Berkeley Lab, received an FLC-2000 Awards for Excellence in Technology Transfer.* The award was given to Dr. Chu for his

* The Federal Laboratory Consortium (FLC) was organized in 1974 and formally chartered by the Federal Technology Transfer Act of 1986 to promote and to strengthen technology transfer nationwide. Today, more than 700 major federal laboratories and centers and their parent departments and agencies are FLC members. A panel of tech transfer experts from industry, state and local government, academia, and the federal laboratory system judge the nominations. One of the most coveted awards in the tech transfer field, the FLC Awards for Excellence

accomplishment in transferring the DOE-developed proton therapy technology to the private sector, including the work done in this CRADA. This year there were 26 projects from 18 laboratories receiving Awards.

In the letter of commendation (May 10, 2000) to Dr. Chu, the Secretary of Energy Bill Richardson said, “Your accomplishment in the development of the Accelerator-Based Particle Therapy to Safely Destroy Cancerous Tumors and the promotion of its use in hospital-based medical accelerators has greatly enhanced the future development of proton therapy technologies. Your subsequent efforts in the cooperative agreement to establish the Northeast Proton Therapy Center at Massachusetts General Hospital in Boston will provide the environment for the production of the most technologically advance products in this field of proton therapy.”

Publications related to the CRADA:

W. T. Chu, “Instrumentation for Medical Beams,” *Proc. of the Beam Instrumentation Workshop, Vancouver, 1994* (Ed. G. H. Mackenzie, B. Rawnsley, and J. Thomson), AIP Conference Proceedings **333**, American Institute of Physics, New York, 160-178 (1995).

J. L. Romero, J. H. Osborne, F. P. Brady, W. Caskey, D. A. Cebra, M. D. Partlan, B. Kusko, R. S. King, I. Mirshad, H. Kubo, I. Daftari, and W. Chu, “Patient Positioning for Proton Therapy Using a Proton Range Telescope,” *Nucl. Instrum. & Methods in Phys. Res.* **A356**: 558-565 (1995).

W. T. Chu, “Ion Beams for Cancer Treatment — A Perspective,” *Nuclear Instruments and Methods in Physics Research* **B99**: 835–838 (1995).

W. T. Chu, “Radiation Detectors,” in *Ion Beams in Tumor Therapy* (ed. U. Linz), Chapman & Hall, pp. 234-245 (1995).

W. T. Chu, “Instrumentation in Medical Systems,” *Proc. of the 1995 Particle Accelerator Conference (PAC95), Dallas, TX, May 1-5, 1995*, 2394-2398 (1995).

W. T. Chu, “Instrumentation for Medical Beams,” Beam Instrumentation Workshop, Vancouver, 1994 (Ed. G. H. Mackenzie, B. Rawnsley, and J. Thomson), AIP Conference Proceedings 333, American Institute of Physics, New York, 160-178 (1995).

L. T. Perkins, G. J. De Vries, P. R. Herz, W. B. Kunkel, K. N. Leung, D. S. Pickard, A. Wengrow, and M. D. Williams, “Performance characterization of rf-driven multicusp ion sources,” Rev. Sci Instrum. 67; 1057 (1996).

K. N. Leung, “Radio frequency multicusp ion source development,” Rev. Sci. Instrum., **67**, 1302 (1996).

Y. Jongen, S. Laycock, et al. (IBA); T. Hurn, L. Nissley, E. Hubbard, M. Heiberger, M. Tabor, G. Silke (GA), Toshiki Tachikawa, Masami Sano, et. al. (Sumitomo Heavy Industries), “The Proton Therapy System for MGH's NPTC: Equipment Description and Progress Report,” 1998.

in Technology Transfer recognize individuals within federal labs (and their industry partners) who have done outstanding work transferring federally developed technology from the lab to the marketplace.

W. A. Barletta, W.T. Chu, and K.-N. Leung, "Ion sources for medical accelerators," *Review of Scientific Instruments* **69**: 1085-1087, 1998.

W. T. Chu, "Hadron Therapy" in *Biomedical Uses of Radiation* (ed. W. R. Hendee), Wiley-VCH Publishers, Weinheim, New York, Chichester, Brisbane, Singapore and Toronto, pp. 1055-1132 (1999).

D. Chen, W. Chu, J. James, G. Jones, Y. Lee, K.-N. Leung, R. Low, and D. Williams, "Electrostatic Low Energy Beam Transport (LEBT) System for Proton Therapy," Plasma and Ion Source Group, Lawrence Berkeley National Laboratory, September 1999.

Presentations related to the CRADA:

W. T. Chu, "Instrumentation for Medical Beams," invited talk at the 6th Beam Instrumentation Workshop, Vancouver, Canada, October 2-6, 1994.

W. T. Chu, "Ion Beams for Cancer Treatment — A Perspective," invited talk at *the Thirteenth International Conference on the Application of Accelerators in Research and Industry, Denton, TX, November 7-10, 1994*, Abstracts (Ed. J. L. Duggan and I. L. Morgan), p. 161 (1994).

W. T. Chu, "Proton Accelerators for Cancer Treatment, " invited talk at the Pohang Light Source Laboratory, November 18, 1994, Pohang, Korea.

W. T. Chu, "Cancer Treatment and Heavy Charged-Particle Accelerators," invited talk at *the Annual Meeting of the Korean Society of Radiation Oncology, January 23, 1995, Seoul, Korea*.

W. T. Chu, "Development of Heavy Charged-Particle Medical Accelerators," invited talk at *the Korea Institute of Science and Technology, January 24, 1995, Seoul, Korea*.

B. Chu, C.F. Chan, R. Gough, M. Hoff, K. N. Leung, M. Sarstedt, J. Staples, and M.D. Williams, "A High Current Ion Source and RFQ Accelerator System for Proton Therapy Applications," *22nd PTCOG Meeting, San Francisco, April 24-26, 1995*.

W. T. Chu, "Instrumentation in Medical Systems," invited talk at the Particle Accelerator Conference PAC95, May 4, 1995, Dallas, TX, *Bull. Am. Phys. Soc.* **40**: 1184 (1995).

W. T. Chu, "Particle Accelerators for Cancer Treatment," invited lecture at the Korea Institute of Science and Technology, May 22, 1995, Seoul, Korea.

W. T. Chu, "Proton Medical Accelerators for Cancer Treatment," *the International Conference on Accelerator and Plasma Research, Taejon, Korea, June 21-24, 1995*.

W. T. Chu, "New developments in Clinical Beam Delivery," invited lecture, *Hadrontherapy, Geneva, September 1996*.

J. Flanz, K Gall, M. Goitein, S. Rosenthal, A. Smith (MGH); L. Nissley, G. Silke, T. Hurn, R. Junge, M. Tabor (GA); S. Laycock (IBA); D. Mavriodis, P. Drouet, J. Hintersteiner, S. Dubowsky (MIT), "Design Approach for a Highly Accurate Patient Positioning System for NPTC" presented at PTCOG XXV, 1996.

W. T. Chu, "Relativistic Hadrons - From Cancer Treatment to the Mars Mission," invited Colloquium, Department of Nuclear Engineering, University of California, Berkeley, February 3, 1997.

W. T. Chu, “Instrumentation in Hadron Therapy,” invited tutorial lecture at *the World Congress on Medical Physics and Biomedical Engineering, Nice, France, September 14–19, 1997*.

W. T. Chu, “Proton Therapy Facility Development,” Invited colloquium at the Universita' di Firenze, Florence, Italy, September 1997.

W. T. Chu, “Hadron Therapy,” invited seminar at the Instituto Nazionale Fisica Nucleare (INFN) del Sud, Catania, Sicily, Italy March 6, 1998.

G. Silke, L. Nissley, T. Hurn, Roger Junge (General Atomics); Y. Jongen, S. Laycock (Ion Beam Applications), “An Advanced Six-Axis Patient Positioner for use in Proton Therapy,” presented at the 7th ANS Topical meeting on Robotics and Remote Systems, 1998.

W. T. Chu, “Proton Therapy,” invited lectures, Chang Gung Memorial Hospital, Taoyuen, Taiwan, June 1-5, 1999.

W. T. Chu, “Dose-rate effects and beam scanning,” invited talk presented at the Beam Scanning Workshop at the 30th Proton Therapy Cooperative Group (PTCOG) meeting, Cape Town, South Africa, April 12–16, 1999.

W. T. Chu, “Emittance Requirements of Small Proton Beams,” invited talk, PTGOG XXXI meeting, Bloomington, IN, October 11-13, 1999.

Acknowledgment:

This research was supported by the Laboratory Technology Research Partnership Program (SC–32), Office of Energy Research, US Department of Energy under a CRADA (Cooperative Research and Development Agreement) between Lawrence Berkeley National Laboratory and General Atomics of San Diego, California, under US DOE Contract DE-AC03-76SF00098.